Application of Solar Powered High Voltage Discharge Plasma for NO_X Removal in Diesel Engine Exhaust

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***Abstract*— This paper proposes a compact electric discharge plasma source for controlling NO_x emission in diesel engine exhaust. Boost converter is used to boost to solar powered battery voltage to 24V, further an automobile ignition coil was used to generate the high voltage pulse using fly-back topology. This design is aimed at retrofitting the existing catalytic converters with pulse assisted cleaning technique. In this paper we bring out a relative comparison of discharge plasma and plasma-adsorbent process at different gas flow rates. Activated alumina was used as adsorbent. The main emphasis is laid on the development of a compact pulse source from 12V battery, which is powered by the solar, for the removal of NO_x from the filtered diesel engine exhaust.**

***Index Terms*— Electric Discharge, Non-thermal plasma, NO_x removal, Diesel engine exhaust, Fly-back**

I. INTRODUCTION

In the last few decades, India has witnessed a tremendous boost in industrialization. Due to the large number of industries and also due to the rapid increase in the number of vehicles, the environment around us is getting more and more polluted. More than the industries, it is the vehicles which have degraded the environment. But we cannot curb the growth of industries or that of the vehicles, as India's social and economic well-being is very much dependent on it. However it would not be wise to put India on the global map of industrialization, at the cost of the health of its citizens. Hence continued efforts have been channeled into this stream to reduce the pollutants in the atmosphere but also at the same time, continue the process of industrialization. The industries that are belching out these poisonous gases as well as the vehicles which give out exhaust gas are sources of man-made air pollution. Diesel engines alone account for nearly 48 percent of India's fuel consumption, henceforth contributing significantly to the man-made air pollution. One of the most harmful pollutants present in the diesel exhaust is NO_X. The conventional techniques which are available to control emission now are either difficult to operate or does not satisfy the stringent emission standards. Reducing diesel engine exhaust to meet future emission standards is a challenging task and there is need for better aftertreatment techniques [1]. For controlling NO_X, the electric discharge based plasma is an upcoming technology being used mainly. Till now all the research regarding control of NO_X using electric discharge has been done using conventional DC and rotary spark gap based high voltage power supplies [2, 3]. However these are not feasible for automobiles, because of the large energy and space required. However, Rajanikanth et al have used solar powered high voltage energization for the removal of NO_X [4]. They had developed a power supply which operated from solar powered battery of 12 V. Our paper proposes a fly-back topology based high voltage pulse power supply powered by DC using an auto ignition coil, that will significantly decrease (there by improving) the size and specific energy density needed for a given NO_X removal.

Our work deals with the design of a power supply for generating the high voltage pulses. Here we take into consideration the fact that since this work has been targeted to be used in vehicles for vehicular exhaust control, the vehicle battery cannot be used as the source of the input voltage as it has its own specific functions to handle the power supply. So, a solar powered battery (12V) is used as the source to drive a SMPS based power supply to produce the required high voltage pulses. We mainly concentrate on the fabrication of a 12V to 24V converter and further a converter for 24V to 18 kV, so as to produce the high voltage required for the generation of the discharge plasma. This discharge plasma used for the cleaning of actual diesel engine exhaust. Studies have been carried out at different gas flow rates. Further a cascading of plasma-adsorbent was studied for NO_X removal, as this combination has given good NO_X removal performance at laboratory level [4, 5].

II. DESIGN AND FABRICATION OF HIGH VOLTAGE PULSE SOURCE

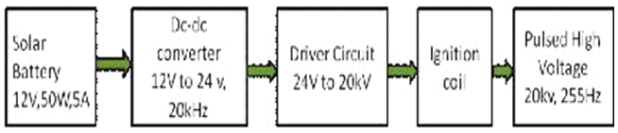

Figure 1. Basic line diagram of the solar powered high voltage power supply

The block diagram for generation of high volatge is shown in Fig. 1. In two stage thedesign and fabrication of solar powered high voltage unipolar pulse has been done. First, the 12V from the solarpowered battery is converted to 24V. Boost Converter has been chosen keeping all parameters and factors in mind. Secondly, the 24V output from

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the boost converter is fed to the ignition coil through driver circuit, which will generate the high voltage pulse. Fly-back topology is used for this generation of high volatge pulse.

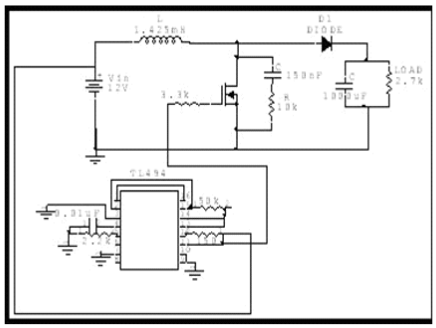

Figure 2. Circuit Diagram of the Boost converter(12V-24V DC)

A. Design of Boost Converter

A boost converter is a power converter with an output DC voltage greater than its input voltage. It is a class of switching-mode power supply (SMPS), in which less number of components is used. Fig. 2 shows the circuit diagram for the boost converter. The basic principle of a Boost converter consists of 2 distinct states:

- In the On-state, the MOSFET is closed, resulting in an increase in the inductor current
- In the Off-state, the MOSFET is open and the only path offered to inductor current is through the flyback diode D_1, the capacitor C and the load. This result in transferring the energy accumulated during the on-state into the capacitor.

Boost converter is designed to operate in discontinuous mode.

B. High Voltage Pulse Generating Circuit

This section describes a laboratory pulse generator using an auto-ignition coil and capable of delivering a train of pulses. The 24 VDC obtained from the boost converter is being used here as input supply. A multivibrator driver circuit makes possible for generation of pulse voltage from an auto-ignition coil. In Fig. 3, free-running variable multivibrator Q_1 and Q_2 drives Q_3, which makes and breaks the primary current to T_1. The high voltage pulse is generated at the end of the period when the circuit is broken and the field of T_1 rapidly collapses through the winding. An unconventional multivibrator circuit was used to provide high saturation currents over a wide range of supply voltage. In this circuit both Q_1 and Q_2 conducting at the same time and both gets cut off at the same time.

Starting with both transistor cut off; C_3 is discharging, its negative plate rising towards ground at a rate determined by various series resistances; while its positive plate is held near zero volts by a relatively low resistance path through R_6 and R_7 and resistance internal to Q_3 across its emitter-base junction. Capacitor C_3 discharges fully and then begins charging in the opposite direction as its negative plate rises above zero volts. When Q_1 and Q_2 begin conducting a positive feedback action is initiated forcing both transistors into saturation. At the same time, transistor Q_3 is turned on by the current supplied through R_6. Duty is determined by the time constant R_5 and C_3 and repetition rate can be varied by changing R_7. When the charging current of C_3 diminishes below the value which will sustain conduction of Q_1, then a regenerative action is again established, this time cutting-off of all three transistors occurs. It is at this moment the high voltage pulse is generated. Fig. 4 shows the waveform of high voltage generated.

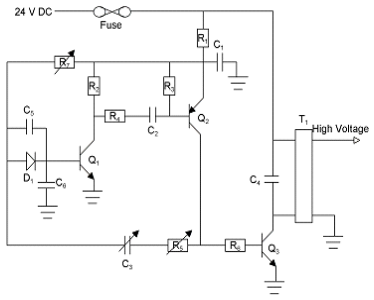

Figure 3. Circuit diagram for generating high voltage pulse from auto ignition coil, C_1 to C_6 = Capacitors, R_1 to R_7 = Resistors, Q_1 to Q_3 = Transistors, D_1 = Diode, and T_1 = Ignition Coil

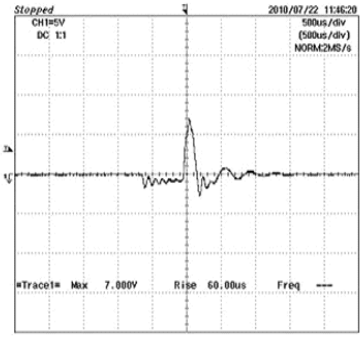

Figure 4. Voltage waveform generated from the new pulse source

III. Design and Fabrication of High Voltage Pulse Source

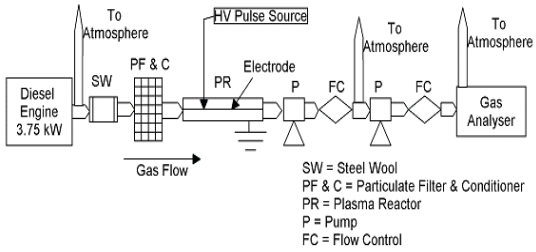

Figure 5. Schematic of experimental setup used for the treatment of exhaust by discharge plasma.

The schematic of experimental setup used during the present research work is shown in Fig. 5. Studies were carried out at the laboratory scale using a diesel generator set as the source of the exhaust and main emphasis has been given on removal of NO_X. Sample gas from the diesel engine exhaust pipe is first allowed to pass through steel wool where the coarse oil mist and dust particulate gets trapped. The sample is then allowed to flow through a conditioning system for filtration of residual water droplets present in the exhaust. The gas is then made to pass through a particulate filter to

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trap solid particles up to the size of 5 ìm. The filtered gas is then treated in various ways and sent to the gas analyzer for analysis of its concentration.

A. Diesel generator

The diesel generator is of 3.75 kW, which is the source for gaseous pollutants. In all of experiments a part of the exhaust is used to study and the remaining is allowed to atmosphere. The flow rate is varied from 2 l/min to 10 l/min using flow control. The diesel engine was operated at 20% and loading was done electrically.

B. Filtering system

To remove soot particle, oil mist from raw exhaust steel wool is used. Filtering system is used to remove moisture, particulate etc from the diesel exhaust. Filtering system consists of steel wool, conditioning unit (UF-10) which has inbuilt particulate filter. Conditioning unit removes the moisture and particulate filter removes the particulate present in exhaust gas. The gas was then carried to the plasma reactor for treatment.

C. Gas measuring system

A gas analyzer is used to measure the concentration of various pollutants present in diesel exhaust gas. In the present case combustion gas analyzer (Quintox-KM9106) is used to measure concentration of NO_X and other pollutants. This combustion analyzer uses a combination of infra-red sensors and electro-chemical sensors for the analysis of different gases in the diesel exhaust.

D. Measuring system

Pulse parameters were measured by using a voltage divider of ratio 2000:1 (EP-50 K, PEEC) and the digital storage oscilloscope (DL 1540: 8 bits 200 MS/s, 150 MHz, Yokogawa). The consumed power was measured from the input side by two reactor principle using a digital wattmeter. To measure power in this method two identical reactors are used. The power consumed by a plasma reactor is the difference of the power given to two identical plasma reactors (say w1) and that given to single plasma reactor (say w2) assuming constant power consumption in the transformer and RSG. The power given to reactor is mathematically denoted by w = (w1"w2).

E. Plasma reactor

Here the conventional wire-cylinder reactor is being used for all of the experiments. This is a dielectric barrier discharge reactor (also called silent discharge reactor) with inner diameter 7 mm and outer diameter 10 mm. The length of the glass tube is 35 cm. It consists of a stainless steel rod of 1.5 mm diameter, acting as high voltage electrode, suspended concentrically in the glass tube. The schematic diagram is shown in Fig. 6. The glass tube was wrapped uniformly with an aluminum foil, which acts as grounded electrode. The aluminum foil is wrapped for the glass tube up to 28 cm length of the tube and thus the effective corona region is only 28 cm.

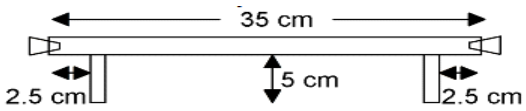

Figure 6. Schematic of plasma reactor

F. Adsorbent reactor

This reactor is made of borosil glass tube with inner diameter 15mm and outer diameter 17mm and effective length of 350 mm. The adsorbent reactor was used along with the plasma reactor. Here in the present work activated alumina is used as adsorbent because of its excellent adsorption capabilities as demonstrated recently [6]. The activated alumina is having a surface area between 100-300 m2/g and pore size of 30-1000 A0.

IV. Results and Discussion

This section presents the results of the experiments carried out at laboratory level using the setup shown in Fig. 5. Studies were carried out with the newly developed compact discharge plasma source. The experiments were conducted with different gas flow rates starting from 2 to 10 l/min at 20% load. The NOX mentioned in the article is the mixture of NO and NO2. The initial concentrations of pollutants are given in Table I.

Finally, the newly built power supply was cascaded with adsorbent to study the enhancement in NO/NOX removal efficiency. Activated alumina has been used as adsorbent.

TABLE I
INITIAL CONCENTRATION OF DIESEL ENGINE EXHAUST

POLLUTANTS	*DIESEL ENGINE AT 20%*
NO	156 ppm
NO_2	18 ppm
NO_X	174 ppm
CO	640 ppm
CO_2	0.0 % vol
O_2	17.5% vol

A. DeNO/DeNO$_X$ efficiency with discharge plasma technique

In this section the newly built high voltage pulse setup was used for generating plasma. The power supply is operated from a DC supply and the output voltage is at 14 kV with a frequency of 2548-252 Hz and rise time of 60 ìsec. The setup shown in Fig. 5 is used for all experiments. The power input to the reactor is 4 watt for three gas flow rates. Conventional wire-cylinder reactor was used as reactor.

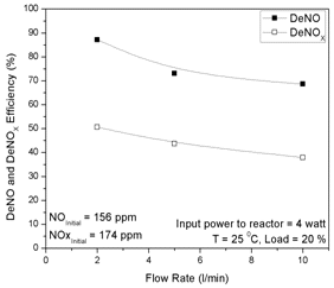

Figure 7. DeNO and DeNO$_X$ efficiency with different gas flow rate

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Fig. 7 shows the variation of DeNO and DeNOx efficiency at various gas flow rates. NO removalefficiency of 87% is achieved with gas flow rate of 2 l/min whereas NOX removal efficiency was 65%.The SED requirement with this gas flow rate comes as 120 J/L. The increase in gas flow rate makes the DeNO and DeNOX efficiency decrease. With gas flow rate of 10 l/min, 68% of NO and 37% NOX removal efficiency is achieved at only 24 J/L.

The removal of NO_X is due to the oxidation of NO to NO_2 by O/O_3 radical and as well as reduction of NO to N_2 by N radicals. In the filtered exhaust plasma treatment, the O radicals effectively help oxidation of NO to NO_2, thus leading to a high NO removal efficiency [7]. The high electric field results in higher energetic electrons. These electrons collide with other background gas molecules, resulting in production of more excited species and ions. However, most of them get quickly converted to radicals [6, 8].

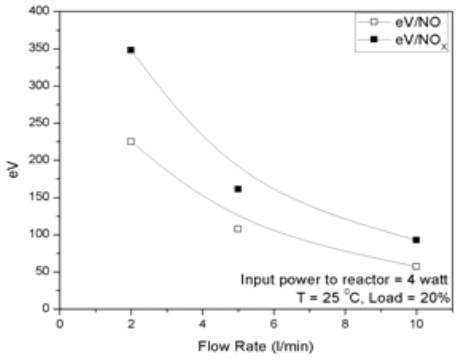

Figure 8. eV/NO and eV/NO_X molecule at different gas flow rate

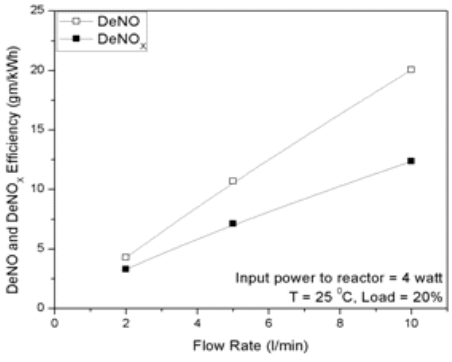

Figure 9. DeNO/$DeNO_X$ efficiency in gm/kWh with different gas flow rate

With industrial point of view it is very much important to know the energy needed for NO and NO_X molecule to be removed. The eV/NO and eV/NO_X can be calculated using the following formula:

$$\text{Energy Cost Per NO Molecule} = \frac{\text{power input to reactor} \times 6.25\times10^{18}\,\text{eV/sec}}{\text{NO Molecule Removed}}$$

Where

$$\text{NO Molecules Removed} = \eta_{DeNO} \times NO_{Initial}\,(\text{ppm}) \times 10^{-6} \times 2.45 \times 10^{19}\,(\text{molecules/cc}) \times \text{gas flow (cc/sec)}$$

$$\text{Energy Cost Per } NO_X \text{ Molecule} = \frac{\text{power input to reactor} \times 6.25\times10^{18}\,\text{eV/sec}}{NO_X \text{ Molecule Removed}}$$

W here

$$NO_X \text{ Molecules Removed} = \eta_{DeNO_X} \times NO_{Initial}\,(\text{ppm}) \times 10^{-6} \times 2.45 \times 10^{19}\,(\text{molecules/cc}) \times \text{gas flow (cc/sec)}$$

T

The eV/NO and eV/NO_X molecule at different gas flow rate is shown in Figure 8. It is seen that with increase in gas flow rate the eV/NO and eV/NO_X decreases because eV required per molecule to be removed is indirectly

proportional to the gas flow rate. From Fig. 8, it is evident that 57 eV is required for removal of one NO molecule at gas flow rate of 10 l/min, whereas 92 eV is required to remove one NO_X molecule.

The $DeNO_X$ and DeNO efficiency in g per kWh can be calculated as follows:

$$\eta_{NO(g/kWh)} = 4.5 \times \frac{\text{NO Removed in ppm}}{\text{SED (J/L)}}$$

$$\eta_{NO_X(g/kWh)} = 4.5 \times \frac{NO_X \text{ Removed in ppm}}{\text{SED (J/L)}}$$

Fig. 9 shows the DeNO and $DeNO_X$ efficiency in gm/kWh. It is seen from Figure 6 about 20 gm of NO and 12 gm of NO_X can be removed per kWh at gas flow rate of 10 l/ min. This amount comes down when gas flow rate are low. This happens because NO and NO_X removal in gm per kWh is indirectly proportional to specific energy density which increases when the gas flow rate becomes less.

A comparative analysis to asses the performance of our newly developed power supply is made in the following section.

B. DeNO/$DeNO_X$ efficiency with cascaded plasma-adsorbent technique

This section gives the comparison of NO and NOx removal efficiency attained with non-thermal plasma and cascaded plasma-adsorbent technique. Plasma cascaded with adsorbents is gaining lot of importance because of its potential applications in removing NO and NOX from diesel engine exhaust. Individually plasma or catalyst or adsorbents cannot exhibit a high NOX removal from diesel exhaust. However, when they are cascaded, better NOX removal can take place. The reason behind this is the production of NO2 from NO in plasma environment which can be taken care by adsorbents and/or catalysts. Various studies have been conducted on NOX removal from synthetic gases using hybrid plasma-adsorbent [9–12] and plasma-catalyst reactors [13]. Studies have also been conducted on actual diesel exhaust [6] using cascaded technique. This is important as the performance of plasma and adsorbents depend on the loading i.e. on the initial concentration of the pollutants. In the present plasma-adsorbent study filtered diesel exhaust is used in a cascade mode by first subjecting the exhausts to the plasma process and then treating them with adsorbents where pollutant removal is effectively accomplished by physical adsorption. The capability of an adsorption process depends on the type of adsorbent material used. Here activated alumina has been used as the adsorbent.

During the experiment power input to the reactor was 4 watt. For experimental purpose filtered diesel exhaust has been used. Fig. 10 shows the DeNO and DeNOX

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efficiency for different gas flow rate. It can be seen that the NOX removal efficiency with cascaded plasma-adsorbent technique is almost constant with different gas flow rate. The DeNO efficiency at all gas flow rate has shown 100% removal due to excellent adsorption property of activated alumina. DeNOX efficiency achieved is 91% at gas flow rate of 2 l/min as shown in Fig. 10, which decreases to only 84% while the gas flow rate is increased from 2 l/min to 10 l/min.

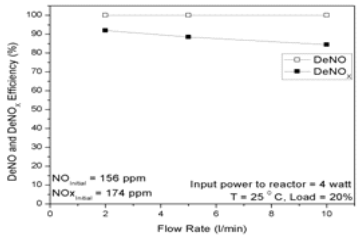

Figure 10. DeNO and DeNO$_X$ efficiency with different gas flow rate

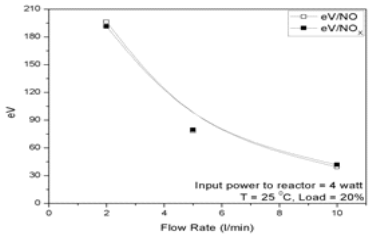

Figure 11. eV/NO and eV/NO$_X$ molecule at different gas flow rate

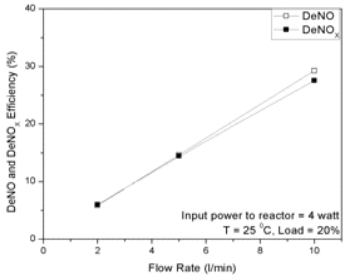

Figure 12. DeNO/DeNO$_X$ efficiency in gm/kWh with different gas flow rate

Fig. 11 shows the eV required to remove one NO/NOX molecule. It is seen that eV required for the removal of one NO/NOX molecule is almost same for all gas flow rate starting from 2 to 10 l/min. This happens because DeNO and DeNOX efficiency is close to each other. It is evident from Fig. 11, 39 eV is required for removal of one NO molecule whereas about 41 eV is required to remove one NOX molecule with a gas flow rate of 10 l/min. NO/NOX removal in gm/kWh can be seen in Figure 12. The amount of removal increases with increases with increase in gas flow rate. This happens because the increase in gas flow rate dominates the decrease in removal efficiency. Here in Fig. 12, it is seen that the amount of removal for NO and NOX in gm/kWh is nearly same for all three gas flow rates. 29 gm of NO and 27 gm of NOX can be removed with a gas flow rate of 10 l/min.

Conclusions

In this paper we have successfully designed a pulse power supply for a possible retrofit in the vehicle. Though we have used a fixed solar panel for powering the 12V battery, it can be obtained from commercially available flexible solar sheets, which can be used on top of the vehicle with proper mechanical fixtures. However, it needs modification on the reactor and on the plasma side to ccommodate the actual exhaust flow-rate and temperature. The electric discharge due to custom made fly-back shown

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